PERFORMANCE OF BLAST-DAMAGED STEEL CONNECTIONS IN PROGRESSIVE COLLAPSE

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ABSTRACT: In progressive collapse events initiated by explosive threats, damage to some connections from blast loading of the structure is likely. In this paper, the results from ten tests of blast-damaged and undamaged beam-to-column connections are examined. An evaluation procedure leading to comparisons of performance based on rotational capacity of both blast damaged and undamaged capacity is presented.

INTRODUCTION

Connections in steel buildings provide much of the structural continuity, redundancy, and ductility required to resist progressive collapse. Premature connection failure causes structural discontinuities and reduces resistance provided by redundant load paths. Furthermore, brittle connections prevent structural members from developing their full ductility, which is critical to arresting the accelerated mass of a building in a progressive collapse event. Therefore, an accurate understanding of connection performance is essential to structural analysis for progressive collapse.

To better understand connection performance in progressive collapse, a series of push-down tests of blast-damaged and undamaged beam-to-column connections were performed (1). Ten connections representing five connection types were tested. These tests were part of a multi-phase program including blast tests of steel columns and base plates (2,3).

In this paper, the multi-phase test program is briefly discussed, with an emphasis on the beam-to-column connection tests. The evaluation procedure used to analyze connection performance is then illustrated for one of the ten connections. Connection performance is compared by type based on rotational capacity. Finally, conclusions are drawn from the discussion.

TEST PROGRAM

The objective of the test program was to determine the response of steel columns, base plates, and beam-to-column connections to blast loading and the effect of blast loading on the post-blast performance of connections. These tests consisted of four phases. In Phase I, the objective was to study the response of typical and blast-resistant base plate connections to blast loading. Phase II was a study of the response of steel columns to blast loading.

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14. ABSTRACT
In progressive collapse events initiated by explosive threats, damage to some connections from blast loading of the structure is likely. In this paper, the results from ten tests of blast-damaged and undamaged beam-to-column connections are examined. An evaluation procedure leading to comparisons of performance based on rotational ca-pacity of both blast damaged and undamaged capacity is presented.

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In Phase III, six specimens representing four types of beam-to-column connections were subjected to blast loading. The connections joined spandrel beams to a single column, as shown in Figure 1, which is a plan view for the steel frames and reaction structure used for Phase III and IV. For all Phase III tests, concrete cladding was added to the frames to simulate in-service conditions for blast-pressure collection.

In Phase IV, the blast-damaged connections from Phase III were loaded quasi-statically to failure. Measurements included the vertical displacement of the connection, downward load in the actuator, axial force in the spandrel beams, and strain in the spandrel beams. For comparison, four connections not subjected to blast loading were also tested. Therefore, Phase IV consisted of ten specimens, five types of connections. A summary of the connections tested in Phase III and IV is provided in Table 1. For reference, the table includes the ASCE 41-06 classifications for the connections (4).

Table 1. Summary of Phase III and IV Tests

Test No.	Connection Type	Beam Size	ASCE 41-06 Classification	Test Phase
1	Traditional Seismic Moment	W18x35	FR[2]-WUF[3]	III,
2	Sideplate® Seismic Moment	W18x35		III,
3	Coverplate Wind Moment	W16x26	FR-Welded Coverplated	III,
4	Traditional Seismic Moment	W18x35	FR-WUF	III,
5	Sideplate® Seismic Moment	W18x35		III,
6	Traditional Seismic Moment	W18x35	FR-WUF	IV
7	Sideplate® Seismic Moment	W18x35		IV
8	Coverplate Wind Moment[1]	W16x26	FR-Welded Coverplated	IV
9	Bolted Shear Tab	W16x26	PR[4]-Shear w/o Slab	IV
10	Bolted Split Tee	W18x35	PR-Double Split Tee	III,

[1]*Connection had extra transverse welds on both bottom coverplates joining the coverplates to the bottom flanges of the spandrel beams.*

[2]*Fully restrained*

[3]*Welded Unreinforced Flange*

[4]*Partially restrained*

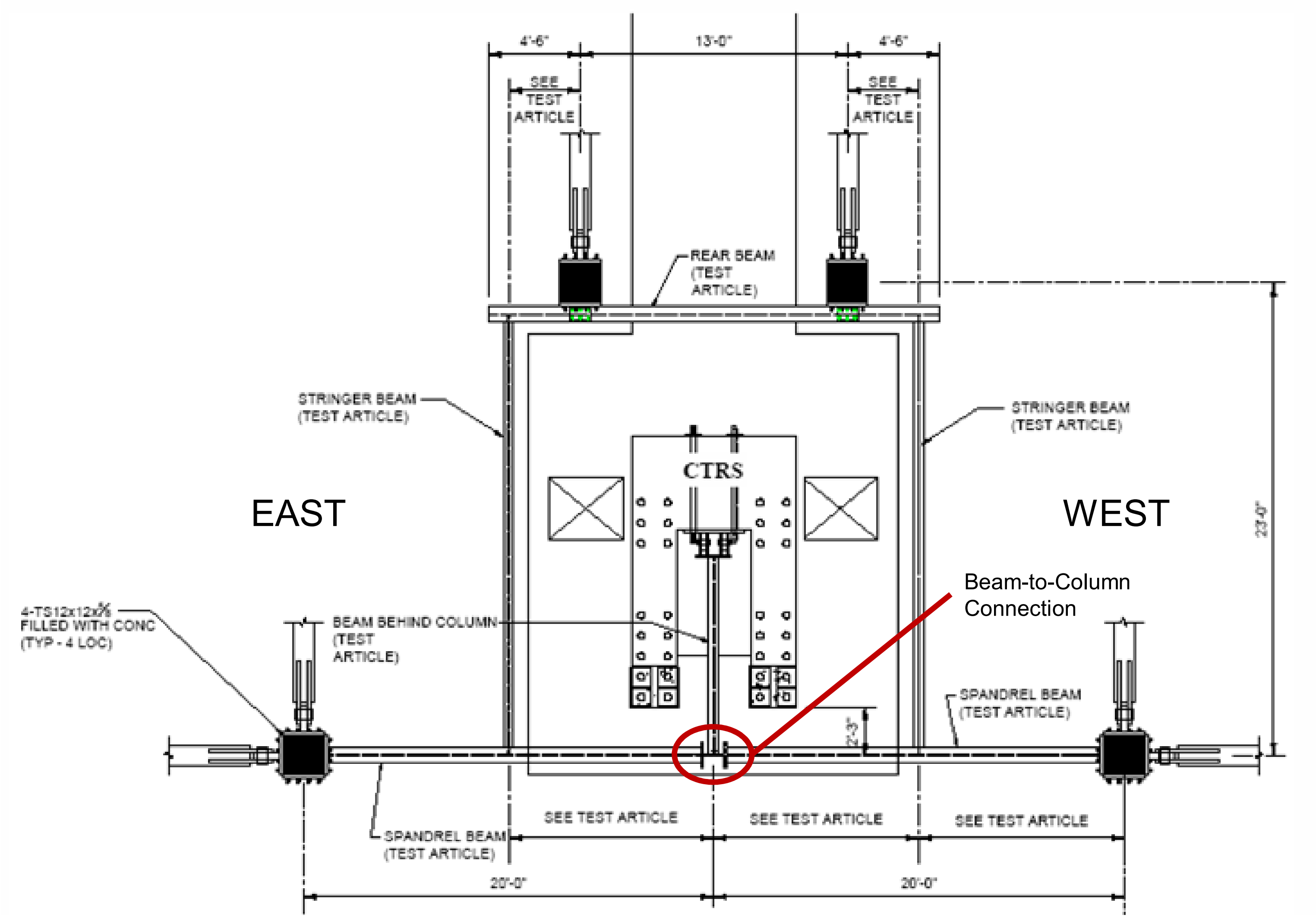


Figure 1. Plan View of Steel Frame for Phase III and Phase IV Tests (1)

EVALUATION PROCEDURE

An evaluation procedure was applied to all ten Phase IV tests. The steps of this procedure are illustrated below for test no. 4, a traditional seismic moment (WUF) connection subjected to blast loading.

The downward force applied to the column versus the Phase IV chord rotation is shown in Figure 2. The chord rotation was determined using the arctangent, as illustrated in Figure 3, because the beams reached relatively large rotations. For all connections, the initial Phase IV position of the connection was taken to be the post-blast final position from Phase III, i.e., a rotation of zero in Figure 2 corresponds with the chord rotation of the beam after blast loading. The rotations where connection articles (bolt or flange) failed are identified in Figure 2. The connection at ultimate failure is shown in Figure 4. The axial force in the spandrel beams was calculated using both load pins and strain gages, and the results of both calculations are shown in Figure 2. Because for most specimens, the load-pin results were more consistent than the strain-gage results, all conclusions were based on the load-pin calculations.

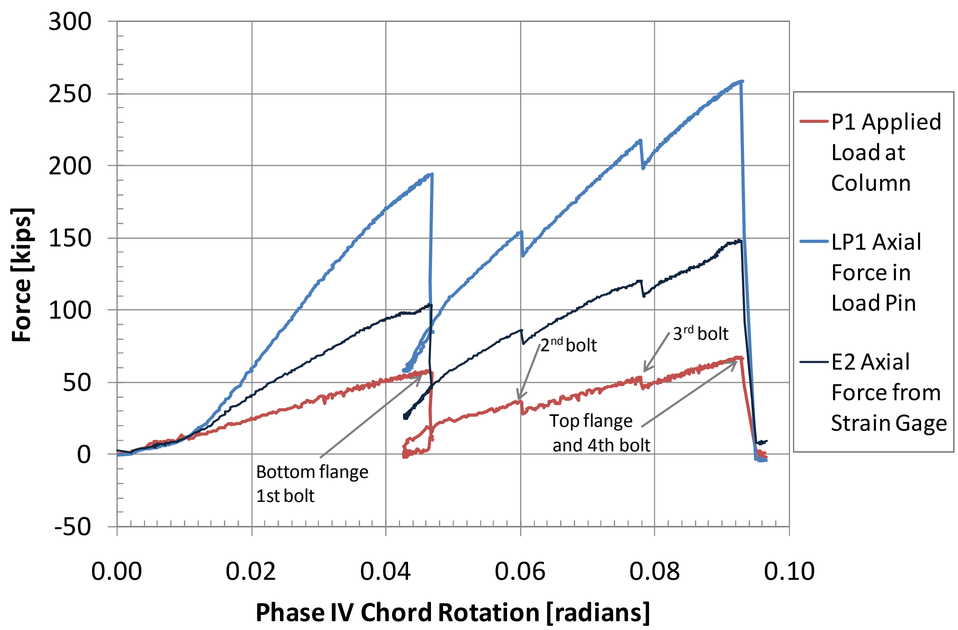
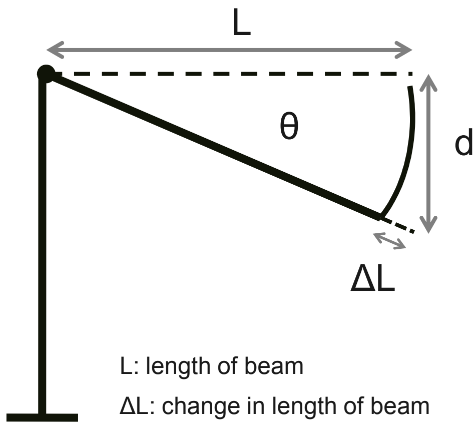


Figure 2. Traditional Seismic Moment (WUF) Connection: Applied and Axial Force Versus Phase IV Chord Rotation



L: length of beam

ΔL: change in length of beam

d: displacement of connection

θ: chord rotation of beam

$$\theta = \arctan\left(\frac{d}{L}\right)$$

Figure 3. Geometric Parameters of Frame Deformation

Figure 4. Traditional Seismic Moment (WUF) Connection at Ultimate Failure (5)

The moment at the connection was calculated by taking equilibrium of the spandrel beam about the connection. The moments calculated from both the load-pin and the strain-gage data are shown in Figure 5. Article failures are labeled, and the rotations where failures occurred are identified by vertical dashed lines. The initial failure (bottom flange and first bolt) takes place at 0.047 radians. Thereafter, the second and third bolts from the bottom fail at 0.060 and 0.078 radians, respectively. Finally, the top flange and fourth bolt from the bottom fail at 0.092 radians. The stiffness of the W18x35 beam is included for comparison.

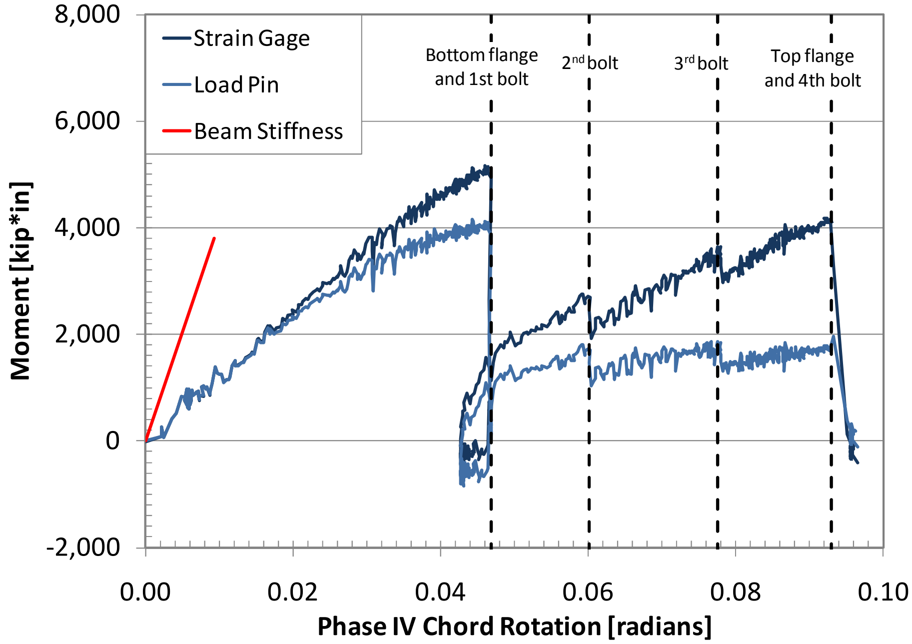


Figure 5. Traditional Seismic Moment (WUF) Connection: Moment Versus Phase IV Chord Rotation

ROTATIONAL CAPACITY BY TYPE

To characterize rotational capacity by connection type, 80%-failure rotations (80% of the rotation at first article failure) were calculated for each specimen and averaged for each connection type. For the traditional seismic moment (WUF) connection discussed above, the 80%-failure rotation was 0.80 x 0.047 = 0.038. This 80% value was taken to be a reasonable limiting rotation to develop the flexural capacity of the structure within a margin of safety. A larger rotation would increase the possibility of the first failure of a bolt or weld, which could introduce unpredictable loads into the structure.

The results of these calculations are shown in Figure 6. The number of specimens for each connection type is shown on the *average* bar for that type; this convention is retained throughout this section, for all bar graphs. The minimum 80%-failure rotation of each type is also included, for comparison. Note that these specimens include both blast-damaged and pristine connections.

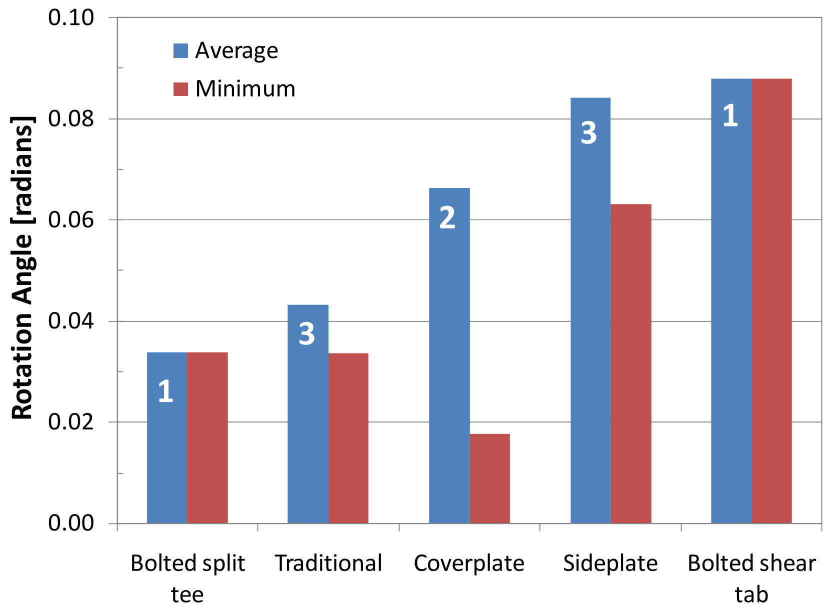


Figure 6. Average and Minimum of 80%-Failure Rotation, by Connection Type

As shown in Figure 6, the bolted shear tab and Sideplate® connections have the highest rotational capacities. The traditional seismic moment (WUF) and bolted split tee connections have the lowest rotational capacities. The coverplate connection has an intermediate capacity, with the minimum significantly less than the average. Many of the differences between the coverplate specimens, noted here and below, were likely due to a fabrication difference and blast damage and may not be inherent to the connection type. Specifically, the bottom flange of the beam joining the blast-loaded coverplate connection was damaged in the Phase III test, weakening it for Phase IV; the coverplate connection not subjected to blast-loading had an extra transverse weld (6).

To assess the effect of blast loading on rotational capacity, 80%-failure rotations of blast-damaged and undamaged connections were compared. For two connection types—the traditional seismic moment (WUF) and Sideplate® connections—two specimens were subjected to blast loading. The rotations of these replicates were averaged and the results are shown in Figure 7. From the figure, blast loading decreased the rotational capacities of all connections but caused the largest decrease in the case of the coverplate connection.

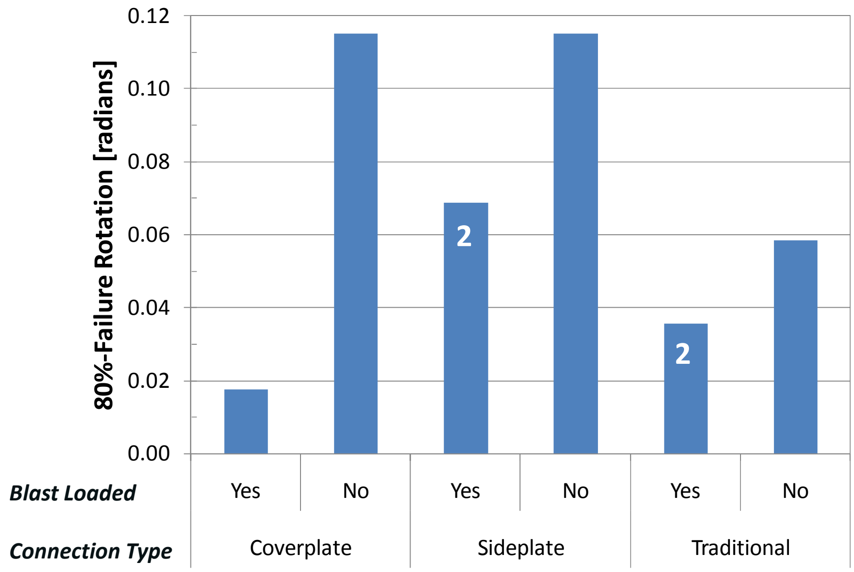


Figure 7. Effect of Blast Loading on 80%-Failure Rotation, by Connection Type

CONCLUSIONS

The test data and subsequent evaluations provide insight into the relative performance of the five connection types. The most important measure of performance is rotational capacity because if a structure lacks ductile connections, it will likely lose structural continuity, increasing the probability of progressive collapse. Additionally, ductile, fully restrained moment connections can develop full member capacity over relatively large deformations, can absorb significant amounts of energy associated with gravity induced accelerations and can reduce potential for collapse. The Sideplate® connection is a good example, as it exhibited the second largest rotational ductility of all the connections tested. Partially restrained connections exhibiting significant ductility (large rotations), while not contributing significant member capacity, can ensure continuity. The bolted shear tab had the largest rotational capacity, but the bolted split tee connection had relatively low rotational capacity. For the coverplate, Sideplate, and traditional seismic moment (WUF) connections, blast loading was found to reduce rotational capacity. Finally, it bears noting that a limited number of tests were performed, some without replicates, and it is recommended that additional testing be performed on the connections discussed here as well as additional connections that are commonly employed.

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